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13. ABSTRACT (Maximum 200 words)
In this project, a new cone penetration test (CPT) method for the determining the hydraulic properties of unsaturated soil was developed. A modified cone penetrometer (cone permeameter) is used to inject water into the soil under constant pressure through a screen and measure movement of the wetting front with tensiometer rings. An inverse methodology is used to analyze the cumulative inflow volume and pressure head readings to obtain estimates of the hydraulic conductivity and soil-moisture retention curves for the soil. To accomplish the inversion, a cone permeameter test is numerically simulated with the radially symmetric form of Richard's equation and the van Genuchten hydraulic conductivity and moisture retention functions. An objective function expressing the differences between flow responses measured with the cone permeameter and those predicted using the numerical model with the parameterized soil hydraulic properties is minimized to obtain the hydraulic parameter estimates. Full-scale tests in a laboratory aquifer and field tests were performed during the course of this study. Excellent agreement between saturated hydraulic conductivity values obained with the cone permeameter and values from in-situ Guelph permeameter and laboratory falling head tests was obtained. Soil-moisture retention curves were similar to those obtained from multi-step outflow and capillary rise tests.

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HYDRAULIC CONDUCTIVITY MEASUREMENT IN UNSATURATED SOILS WITH A MODIFIED CONE PENETROMETER

Final Report
ARO Young Investigator Program
Army Research Office

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STATEMENT OF THE PROBLEM STUDIED

A new in situ method for characterization of unsaturated soil hydraulic properties was studied. Knowledge of these soil properties is necessary for predicting the movement of water and water-borne contaminants from surface and near-surface sources to groundwater, design of bioremediation systems, prediction of infiltration capacity, and determining the susceptibility for landslides and floods. Many existing approaches for measurement of hydraulic properties in unsaturated soils are limited to near-surface application and require augering a borehole, which may result in contaminated soil being brought to the surface. In this project, a new cone penetrometer test (CPT) method for determining the hydraulic properties of unsaturated soils was developed and tested. While CPT methods exist for measurement of the hydraulic conductivity of saturated soil, no methods were previously available for determination of the soil-moisture characteristic curve and hydraulic conductivity function of unsaturated soils. This work is important because CPT methods for site exploration are preferred at contaminated sites. CPT methods do not produce soil cuttings at the surface, and can provide more rapid characterization of the subsurface than traditional methods. Given the potential of this new CPT method for expedited site characterization, this work directly supports the Army's needs improved methods for characterizing and remediating its contaminated sites.

RESEARCH OBJECTIVES

The overall goal of this project was to develop a CPT-based methodology for investigating the fundamental relationships between measurable transient unsaturated flow responses and soil hydraulic parameters. Specific objectives of this work included 1) designing a modified cone penetrometer (called a cone permeameter) to inject water into to subsurface and measure pressure head responses, 2) creating an inverse methodology for estimating hydraulic properties of unsaturated soils from cone permeameter data, 3) demonstrating the performance of a prototype via carefully controlled full-scale laboratory tests, and 4) testing the methodology and instrumentation in the field.

BACKGROUND

The cone permeameter was designed to determine the soil water retention curve, $\theta(h)$, the relationship between the water content and the pressure head of an unsaturated soil, and the unsaturated hydraulic conductivity function of the soil, expressed in terms of pressure head or water content, $K(h)$ or $K(\theta)$. Knowledge of these curves is required for accurate numerical modeling of variably saturated flow. The van Genuchten (1980) analytical functions are commonly used to describe these hydraulic properties:

$$\theta_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \frac{1}{(1+|\alpha h|^n)^m}, \quad h<0$$
$$\theta_e = 1, \quad h \geq 0 \tag{1}$$

$$K(h) = K_s \theta_e^l \left[1-\left(1-\theta_e^{1/m}\right)^m\right]^2 \quad h<0$$
$$K(h) = K_s, \quad h \geq 0 \tag{2}$$

where θ_e is the effective water content (L^3L^{-3}), θ_r and θ_S are the residual and saturated water contents (L^3L^{-3}) respectively, α (L^{-1}), n and m (=1-1/n) are empirical fitting parameters (-), K_S is the saturated hydraulic conductivity (LT^{-1}) and l is the pore connectivity parameter (-). The pore connectivity parameter, l, is commonly set equal to 0.5 (Mualem, 1976).

To develop a CPT tool and methodology for determining the soil hydraulic properties $K(h)$ and $\theta(h)$ for vadose zone soils, the cone permeameter was designed to inject water into the soil under constant pressure through a screen and to measure movement of the wetting front with tensiometers above the screen (Figure 1) (Leonard, 1997; Gribb et al., 1998). The parameters describing the $K(h)$ and $\theta(h)$ relationships are determined via analysis of cumulative inflow volume and pressure head readings using an inverse solution technique. To accomplish the inversion, a cone permeameter test is numerically simulated with the radially symmetric form of Richards equation and the van Genuchten (1980) functions of $K(h)$ and $\theta(h)$:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\,K\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right] \tag{3}$$

Then an objective function, Φ, expressing the differences between flow responses measured with the cone permeameter and those predicted using the numerical model with parameterized soil hydraulic properties, is minimized:

$$\Phi(b,q,p) = \sum_{j=1}^{m_q} v_j \sum_{i=1}^{n_{qj}} w_{i,j}\left[q_j^*(x,t_i) - q_j(x,t_i,b)\right]^2 + \sum_{j=1}^{m_p} \bar{v}_j \sum_{i=1}^{n_{pj}} \bar{w}_{i,j}\left[p_j^*(\theta_i) - p_j(\theta_i,b)\right]^2 \tag{4}$$

where the first term on the right side represents deviations between measured and predicted space-time variables (e.g., pressure heads or moisture contents at different locations and/or times, or the cumulative infiltration rate versus time). In this term, m_q is the number of different sets of measurements, and n_{qj} is the number of measurements in a particular measurement set. Specific measurements at time t_i for the jth measurement set at location $x(r, z)$ are represented by $q_j^*(x, t_i)$, $q_j(x, t_i, \boldsymbol{b})$ are the corresponding model predictions for the vector of optimized parameters $\boldsymbol{b}$ (e.g., θ_r, θ_s, α^w, α^d, n, K_s), and v_j and $w_{i,j}$ are weights associated with a particular measurement set or point, respectively. The weighting factor, v_j, is given by the inverse of the number of measurements multiplied by the variance of those observations, and $w_{i,j}$ is equal to 1 in this work. The second term on the right represents differences between independently measured $p_j^*(\theta_i)$ and predicted $p_j(\theta_i, \boldsymbol{b})$ soil hydraulic properties (e.g., $\theta(h)$, $K(\theta)$ or $K(h)$ data), while the terms m_p, n_{pj}, v_j and $w_{i,j}$ have similar meanings as for the first term, but are now for the soil hydraulic properties. Minimization of the objective function Φ is accomplished by using the Levenberg-Marquardt nonlinear minimization method (Marquardt, 1963), which combines the Newton and steepest descent methods.

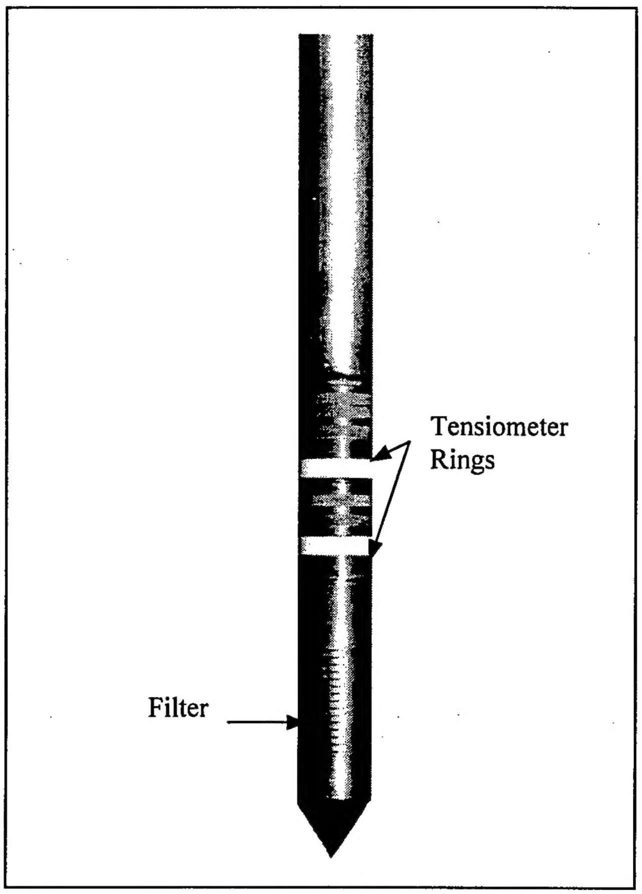

Figure 1. Prototype cone permeameter.

Summary of the Most Important Results

The project objectives described above were met via a fully integrated numerical and experimental research program. Numerical studies were undertaken to investigate the effects of varying hydraulic soil properties and test conditions on observed flow responses. A fully functional prototype cone permeameter and data acquisition system were designed and fabricated. Full-scale soil tank experiments were performed to assess the validity of the numerical model predictions and the applicability and ease of use of the prototype in sandy soil (Gribb et al., 1998; Kodesova et al., 1998a,b, 1999a; Šimůnek et al., 1999) (Figure 2). Finally, a field demonstration of the prototype was completed (Kodesova et al., 1999b). The information gained on unsaturated flow processes through this work provides the basis for future work with other soil types, and investigations into the effects of soil anisotropy and disturbance due to cone penetration. Specific results include are as follows:

- We modified a standard size cone penetrometer housing to allow injection of water into the subsurface through a screened section at a known pressure and measure the pore water pressure at two locations with tensiometer assemblies (shown in Figure 1). We developed inverse solution methods to predict the soil hydraulic properties from data obtained during transient flow tests and objectives functions of the form shown in Eq. 4 (Gribb et al., 1998; Kodesova et al., 1998b, 1999a).

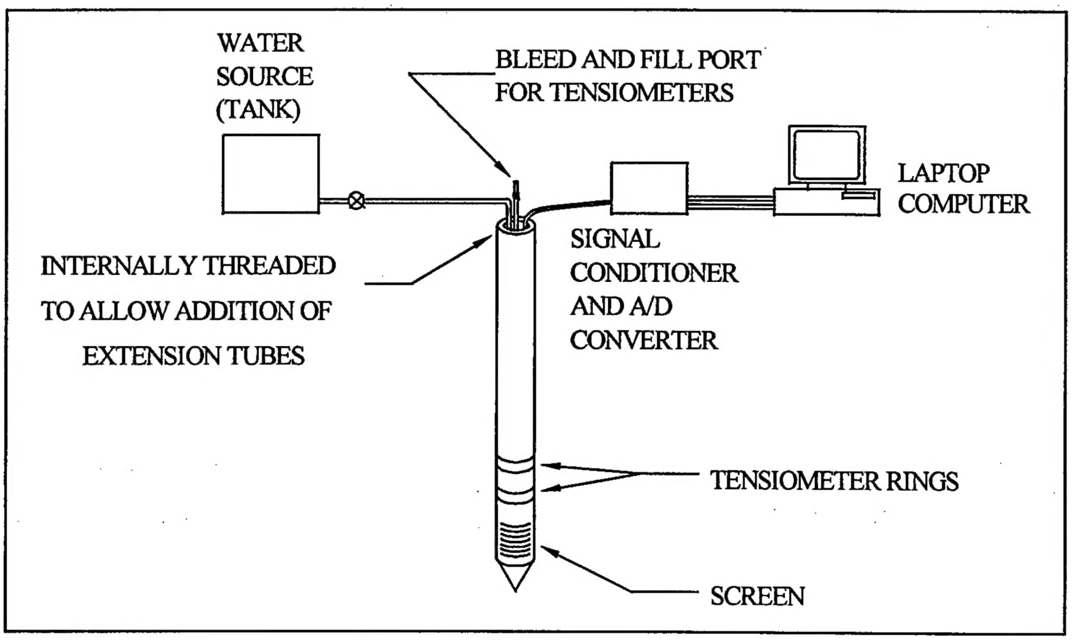

Figure 2. Cone permeameter set-up for laboratory aquifer and field testing.

- We tested the cone permeameter in a laboratory aquifer and compared the results of inversion to results from standard methods including in situ slug tests, and laboratory constant head permeability, pressure plate, capillary rise and hanging column tests. The cone permeameter results compared favorably with results from the standard methods, suggesting that this tool can be used to estimate $K(h)$ and $\theta(h)$ in sandy soil (Gribb et al., 1998; Kodesova et al., 1998a,b, 1999a).

- We then tested the cone permeameter at three sites in a sandy, relatively homogeneous soil (Figure 3). We compared the inversion results to results from standard methods including falling head, pressure plate, capillary rise, and multi-step outflow laboratory tests and in situ Guelph permeameter tests. The cone permeameter results compared favorably with results from the standard methods, suggesting that this tool can be used to estimate $K(h)$ and $\theta(h)$ in sandy in-situ soils. Figure 4 shows test data (cumulative inflow volume and pressure head readings) and simulated results for a single test. The estimated $\theta(h)$ curves with respect to those obtained using the standard methods are shown in Figure 5, and the saturated hydraulic conductivity values obtained from inversion of test data from one location are shown in Table 1. Excellent agreement between the hydraulic conductivity values was obtained (Kodesova et al., 1999b).

- We analyzed the usability/practicality of the prototype and test method and modified the procedure and equipment accordingly. Analysis of the procedure included the impact of cone permeameter placement (pushed vs. buried) and the impact of the initial soil moisture content on estimates of the soil hydraulic properties. We found that the effect of soil densification caused by direct push was minimal, but resulted in slightly lower values of θ_S and K_S than when the prototype was buried prior to testing (Kodešová, et al., 1998a,b) and that additional inputs of initial soil moisture content are helpful for more precise determination of the hydraulic parameters usually investigated (θ_S, θ_r, α, n, and K_S) (Kodešová, et al., 1998b, 1999a). The equipment modifications included modifying the screen to prevent clogging, improving the method of assembly for the tensiometer sections, and devising a method to insert the permeameter into the soil to minimize disturbance.

- We also examined the impact of varying the number of hydraulic parameters to be estimated and found that optimization of additional parameters (l, the pore connectivity factor, and k^A, an anisotropy factor) improved the fit of measured data (Šimůnek et al., 1999; Kodešová, et al., 1999a). We also showed that we can find the wetting branch of soil hydraulic characteristics from the main wetting part of experiment, as well as simultaneously evaluate the wetting and drying curves via analysis of both wetting and redistribution parts of a cone permeameter test (Šimůnek et al., 1999; Kodešová, et al., 1999a).

- In addition to using this method to predict soil hydraulic properties of unsaturated soils, we examined the feasibility of using the cone permeameter and a simplified analysis method to predict the saturated hydraulic conductivity rapidly, while still in the field (currently, the inverse solution is not suited to analysis in real time). We found that the log-transformation of the steady state inflow rate, Q, and the saturated hydraulic conductivity, K_S, yielded a

linear relationship. Comparison of inverse solution results for K_S from the laboratory aquifer and field tests of the cone permeameter with K_S values predicted with this relationship differed by less than a factor of three. Sensitivity analyses showed that this relationship was significantly influenced by the van Genuchten parameters α and n while, but not by the values of θ_r and θ_S. (Al-Houri, 1999). More work is needed on this topic to determine if a reasonably accurate empirical analysis method can be developed. A rapid assessment technique would increase the general usefulness of the cone permeameter by decreasing the computational effort required to analyze the data when only knowledge of K_S is needed.

- The results of the project show that the cone permeameter method can be used to predict the soil hydraulic properties in sandy soils. We have begun field testing the prototype and analysis method in a loamy soil to test the method in soils with greater fines contents. Confirmatory laboratory and field tests are ongoing.

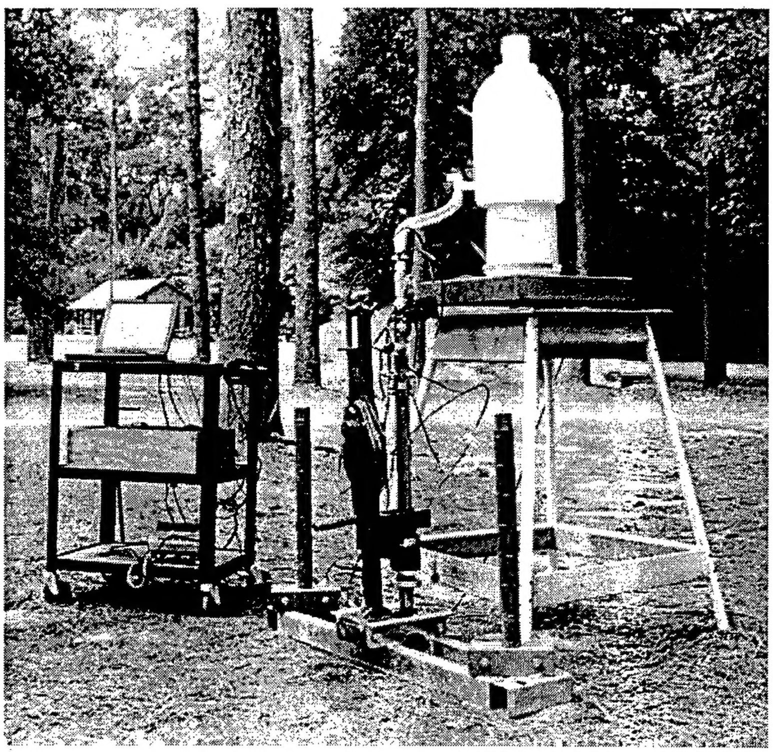

Figure 3. Cone permeameter set up for field testing.

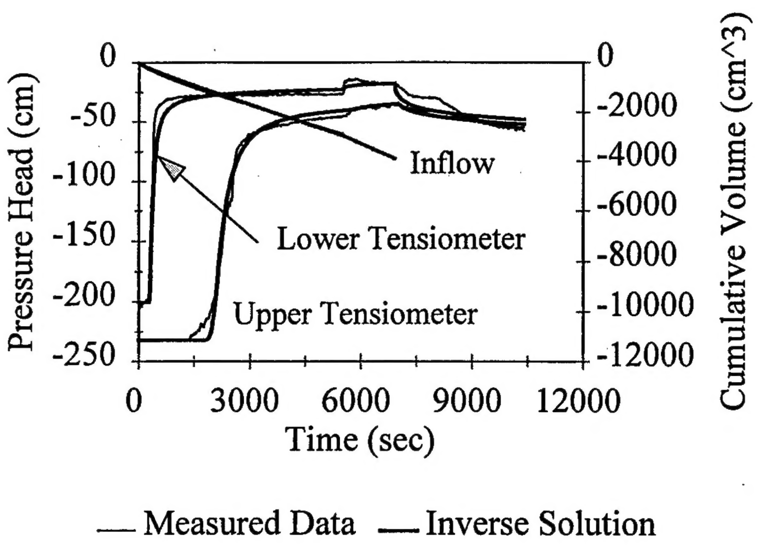

Figure 4. Observed and simulated responses for cone permeameter Test B at Site 1 in Poinsett State Park (Kodesova et al., 1999b).

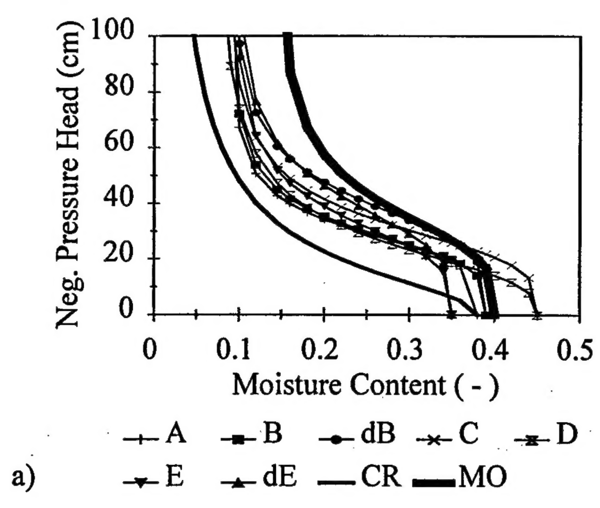

Figure 5. Soil-moisture retention curves resulting from standard methods and inversion of flow data from five cone permeameter tests at Site 1 in Poinsett State Park. Curves A, C, and D are from analysis of the infiltration part of the experiments, while B and E are from both infiltration and redistribution (dB and dE are the drying branches). Curves CR and MO are from capillary rise and multi-step outflow experiments, respectively (Kodesova et al., 1999b).

Table 1. Saturated hydraulic conductivity values obtained via inversion of cone permeameter data and standard test methods (h_0 = supply pressure head value).

Test Method	K_S (cm/sec)
Multi-Step Outflow Tests (2 samples)	0.0012 – 0.0027
Guelph Permeameter Tests (6 locations)	0.0025 – 0.0039
Laboratory Falling Head Tests (9 samples)	0.0013 – 0.0044
Cone Permeameter Test A: h_0 = 30, 50 cm	0.0016
Cone Permeameter Test B: h_0 = 30, 50 cm, & redistribution	0.0016
Cone Permeameter Test C: h_0 = 30, 50 cm	0.0011
Cone Permeameter Test D: h_0 = 21, 108 cm	0.0036
Cone Permeameter Test E: h_0 = 21, 80 cm, & redistribution	0.0010

ARMY RELEVANCE

The products of this research project have the potential to enhance the Army's ability to characterize and remediate contaminated sites. When this technology fully developed, it will have numerous advantages over existing methods for soil hydraulic property measurement. As with other CPT tools, the cone permeameter is minimally intrusive and does not result in the removal of potentially contaminated materials. This feature safeguards the welfare of operating crews and reduces site investigation costs. It is applicable to depths of 30 m or more below ground surface, depending on soil resistance to penetration. Since the analysis is based on transient flow data, time and water requirements are minimized. Finally, the inverse solution approach makes it possible to simultaneously determine the soil-moisture retention and hydraulic conductivity curves in unsaturated soils, something not currently possible with other methods.

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REPORT OF INVENTIONS

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